TRANSACTIONS
OF
The Optical Society.

VOL. XVII. NOVEMBER, 1916. No. 2.

Meeting, 9th November.

F. J. CHESHIRE, Esq., F.R.M.S., President, in the Chair.

The following were balloted for and duly elected Members of the Society, viz. :—

James Weir French, B.Sc., Messrs. Barr & Stroud, Glasgow.

Francis Everard Lamplough, M.A., Messrs. Chance Brothers, Birmingham.

J. Martin Strang, Messrs. Barr & Stroud, Glasgow.

The undermentioned candidates were proposed for election as Members, the name of the proposer, from personal knowledge, being appended :—

F. S. Berrett, East Dulwich (S. D. Chalmers).
Charles Lees Curties, London (T. F. Connolly).
F. S. B. Ellis, West Croydon (F. J. Clatworthy).
J. W. Hasselkus, London (The President).
Herbert Jackson, London (The President).
Horace Lee, Leicester (S. D. Chalmers).
Thomas Ralph Merton, D.Sc., London (The President).
John William Nicholson, D.Sc., London (The President).
L. V. Riquez, Clapham (S. D. Chalmers).
William Simms, Blackheath (Wm. Shackleton).

Proposed for election as Student Member :—

Eric L. Ebbage, Kingston-on-Thames (S. D. Chalmers).

The following paper was read and discussed :—

SOME NOTES ON GLASS GRINDING AND POLISHING.

By James Weir French, B.Sc.

That the polished surface of a piece of glass differs in its physical condition from the original underlying material has been recorded by Lord Rayleigh and subsequent observers.

Sir George T. Beilby, in his series of published papers dealing with the subject of the polished surfaces of metals, has explained how the surface layer is formed. According to this investigator the forces exercised in the rubbing of the surface overcome the crystallic and cohesive forces binding together the surface molecules, which rearrange themselves uniformly under the action of the surface tension forces.

In this way a surface which scatters light, owing to the presence of masses of molecules whose irregularities are great compared with the wave length of light, is converted into a continuous reflecting surface, the irregularities of which are less than a wave length.

When the surface of a piece of metal is scratched a groove is formed as the result of the tearing away of masses of crystals and partly by the swaging of the material. When such a scratched metal surface is polished the grooves become covered over with a continuous surface flow layer and disappear. If the surface is removed by etching the grooves reappear.

The cohesion of the surface flow layer is such that considerable areas can be bridged over. Sir George Beilby originally supposed that the groove became filled with débris, which acted

as a support for the surface layer, but in a paper*, illustrated by beautiful coloured photographs, he has demonstrated that no such supporting débris is necessary. One of these photographs shows a surface pit covered over by a continuous layer, and the absence of supporting débris is evidenced by the variation of the colour of the layer, due to retransmission of light, reflected from the internal surfaces of the pit.

When a polished glass surface is etched by means of hydrofluoric acid, either in the liquid or the gaseous state, or by means of caustic soda, the surface appears covered with innumerable scratches. It has been assumed accordingly that glass behaves in the same general manner as metal when its surface is polished.

It is the purpose of this article to show that the conditions determining the behaviour of glass are very different in certain essential respects from those determining the behaviour of metals.

A simple groove or pit that is comparatively deep with respect to its width can be formed on most metal surfaces as the result of the removal of masses of crystals, or by compression or swaging of the material. This is not possible in the case of a vitreous substance such as unworked glass, in which conchoidal fracture is a characteristic. When an unpolished glass surface is scratched numerous conchoidal splinters are removed, and under the microscope such a scratch appears as an irregular band of conchoidal concavities of considerable width compared with its depth.

Fig. 1 is a photo-micrograph, magnification 250 diameters, of the fine emery-ground glass surface immediately before the first polishing operation with rouge is commenced. It will be seen that there is no evidence of any definite

---

* Proceedings of the Royal Society, A. Vol. 89, 1914.

scratches, such as reappear when the polished surface layer is etched. The tops of the ridges have been focused upon.

If scratches in the glass material were covered over by a surface layer, it is to be expected that

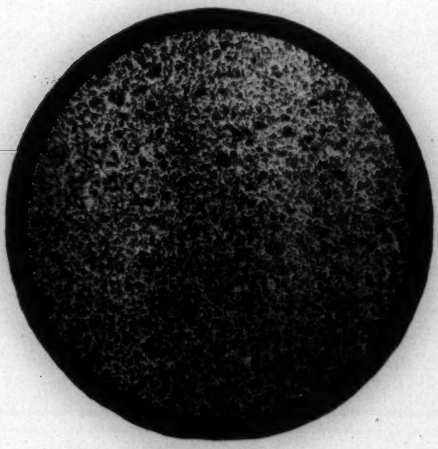

FIG. 1.—MAGNIFICATION 250 DIAMS. TOPS OF RIDGES IN FOCUS.

fine particles of foreign material or débris would be included, but an examination of many thousands of finished glass surfaces has failed to reveal any such included matter.

Attempts have been made by the author to include foreign matter in the irregularities of the glass surface and in fine grooves or sleeks of the polished surface, which will be referred to later, but without success. The finest deposit

of silver in the hollows of a ground glass surface all disappears during the polishing process. The inclusion of foreign matter in fine grooves in polished surfaces has proved to be equally impossible.

Airbells afford a simple means of examining the question of the covering over of pits by the surface layer. For experimental purposes there was made a special piece of glass containing a great number of airbells, varying in diameter from about 0.002 to 0.01 inch. The surface when polished showed pits of numerous sizes. Airbells that were just broken into became filled with rouge and could be easily observed. Very minute holes were formed in the case of the smallest airbells that were just broken into, and an examination of the orifices showed no signs of any continuous bridging over as the result of polishing. In the case of the larger airbells the orifices were comparatively large and more irregular.

It would appear that the cohesion of the silicates constituting glass is too small to permit of any continuous bridging over effect such as is observable in the case of metals in which the cohesion is evidently very much greater.

Notwithstanding the above observation, it is an easily demonstrable fact already well known in most optical factories that when a polished glass surface is lightly etched innumerable fine, clean scratches are exposed. The explanation would appear to be that the essentially fine scratches in question exist only in the surface flow layer of the polished glass. If the scratch penetrates the surface layer its outline becomes irregular, due to the conchoidal splintering of the material.

In the workshop two kinds of scratches are recognised; one exhibiting irregular fractures is called a *cut*, and the other, having clean, well defined edges, is called a *sleek*. The term "scratch" is rarely used except in a very general sense. For purposes of explanation, the

original glass will be called Alpha glass, and the modified material, such as the surface layer, will be called Beta glass. The result of the present investigation would seem to indicate that a cut is a scratch in the Alpha glass and that a sleek is a scratch in the Beta glass.

From a comparison of fig. 2, which represents a typical sleek magnified 230 fold, and fig. 3,

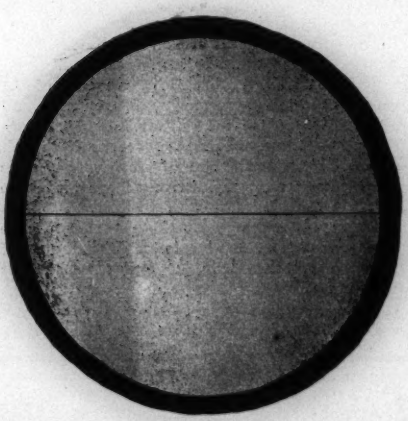

FIG. 2.—MAGNIFICATION 230 DIAMS.

which is a photograph of a cut magnified 50 fold, it will be seen that the characteristic differences are very definite. Material has evidently been ploughed uniformly from a surface layer of a comparatively amorphous substance in the formation of the sleek, whereas material has been burst irregularly from a more brittle substance in the formation of the cut.

Fig. 2 is a very perfect example of a sleek.

It was obtained, however, from the workshop in the ordinary course of manufacture.

The cut fig. 3 was produced by drawing a hard steel point over the finished glass surface.

It is suggested that the stages in the production of a polished glass surface are as follows :—

In fig. 4, (1) is the metal grinding tool, usually fine grained cast iron; (2) is a hard grain of the loose abrasive, such as carborun-

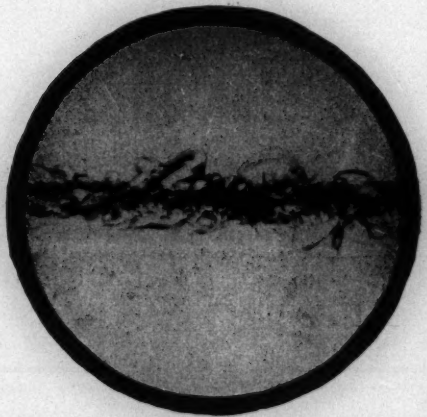

FIG. 3.—MAGNIFICATION 50 DIAMS.

dum; and (4) is the glass being ground. The pressure of (2) is localised at the points of contact of the grain and the glass, with the result that conchoidal splinters are burst off. Portions of these splinters can be recognised in the débris under the microscope. Under the rubbing action of the tool (1) the grain (2) also tears its way through the glass, but the general result is the same production of splinters.

When the abrasive is coarse the pressure of the tool is transmitted to the glass by a comparatively small number of grains and the pressure at the individual points of contact is correspondingly great, with the result that large splinters are produced.

When the abrasive is fine the pressure of the tool is transmitted through a large number of points and the forces are smaller and less material is removed.

If the abrasive is hard and unyielding the intensity of the pressure at the points of contact will be greater than in the case of a softer material, the points of which will yield and distribute the load.

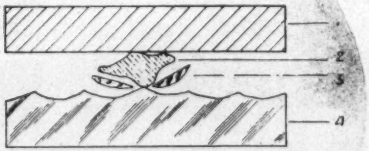

FIG. 4.—(1) GRINDING TOOL. (2) GRAIN OF ABRASIVE. (3) CONCHOIDAL SPLINTERS. (4) GLASS.

From fig. 5 a comparative idea will be obtained of the abrasive effects produced by various grades of abrasives. All three photomicrographs represent the same piece of glass, and in all cases the magnification is 50 diameters. The black masses are the abrasive materials placed on the surfaces.

Sector 1 shows the abrasive effect of carborundum that has passed through a sieve of 80 meshes per inch. Sector 2 shows the effect of emery that has passed through a sieve of 160 meshes per inch. Sector 3 shows the abrasive effect of emery that has not settled in water during a time of 40 minutes. Fig. 1, already referred to, is the same surface, sector 3, magnified 250

FIG. 5.—MAGNIFICATION 50 DIAMS.

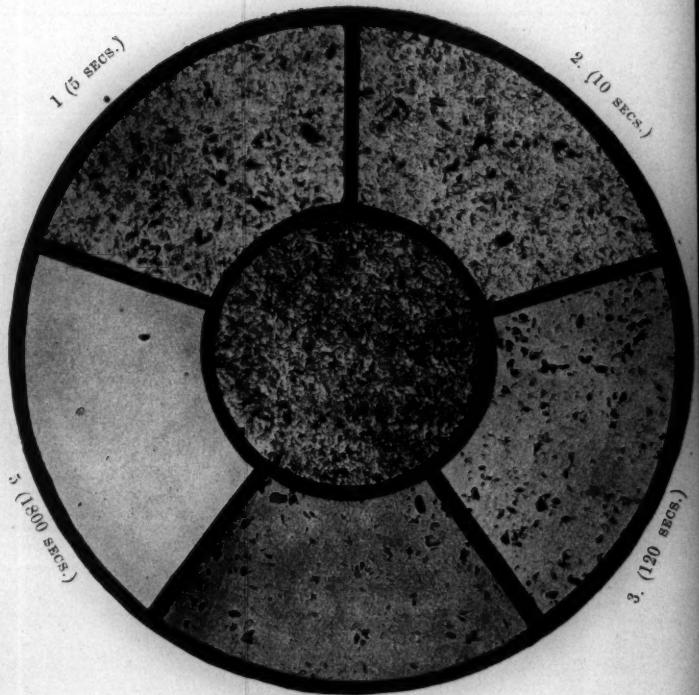

FIG. 6.—MAGNIFICATION 250 DIAMS.

diameters. It shows the stage before the polishing, or, as it is called, the finishing process, is commenced.

In all these rough grinding or smoothing operations with hard abrasives, such as carborundum or emery, the effects are the same throughout. They differ only in degree.

When a splinter is formed the forces at the surface of fracture are probably so great as to overcome the cohesive and crystallic forces. The surface molecules accordingly arrange themselves, under the action of surface tension, and form glazed surfaces. This explanation of the glazed surface of fracture is only advanced as being a possible one. The action probably resembles the fire glazing of glass in which the cohesion of the surface molecules is overcome by heat instead of mechanically. Where two such surfaces intersect the molecules forming the edge rearrange themselves under the action of surface tension and the ridge becomes rounded. Under the microscope such rounded edges have a characteristic green appearance.

The network of rounded edges is clearly indicated in fig. 1, a close examination of which will help one to realise how readily the molecules of glass when disturbed rearrange themselves in a continuous surface form.

Where two ridges intersect there is produced a spot having a continuous reflecting surface. These ridges and spots are the initial stage of the polished surface.

It is important to note that the removal of material and the polishing of the surface occur together even when using the roughest abrasive. The two actions occur together throughout the whole process until the final surface has been produced.

In the early operation the removal of material is very great in comparison with the polishing produced, and in the final stages the removal of material is comparatively small, although it always occurs.

If a surface smoothed with fine abrasive be examined by oblique reflection it will be seen that, although the greater part of the light is scattered, a considerable quantity is reflected. Even a rough ground surface, if carefully viewed, exhibits some reflecting power.

It is remarkable how easily, by the exercise of mechanical force, such as rubbing with a piece of wood with the finger-nail, or even continued rubbing with the finger, the cohesion of the glass molecules can be overcome to such an extent that they can rearrange themselves to form portions of a continuous reflecting surface layer. Something akin to liquefaction may be said to take place, the molecules when disturbed having the power of rearranging themselves, just as in the case of the fire glazing of a surface as the result of thermal agitation of the molecules.

If this effect of mechanical agitation is clearly kept in mind, the next stage in the polishing of a surface will be the more readily understood.

When the polishing tool, which frequently consists of a flat layer of pitch on the face of a metal plate, is rubbed on the glass surface, the portion of glass in immediate contact becomes liquefied, as already explained, to a depth of about 1/4000th to 1/5000th inch (about 1/200th millimeter), and this liquefied surface becomes broken up and detached during the rubbing process. New material is thus exposed to the liquefying action, and is in turn removed. This process repeats itself, *and a perfect surface is only obtained by the removal of material beyond the bottom of the hollows produced in the glass surface during the earlier smoothing process.*

It will be realised how important it is in practical work that in the smoothing process there should be produced no hollows of unusual depth, since to remove such a hollow it is necessary to polish away the whole surface right down to the bottom of the pit.

This is illustrated by the series of photo-

micrographs, fig. 6, which show the results of polishing a smoothed piece of crown glass for various periods. A very hard cloth polisher with rouge as a polishing medium was employed, special care being taken in the regulation of the conditions of working. In all cases the magnification is 250 diameters, and as nearly as possible the same portion of the surface is represented in all the photographs.

The central portion represents the smoothed surface ground with 40 minute emery on a flat cast-iron tool. Sector 1 shows the result of 5 seconds' polishing; sector 2 shows the result of 10 seconds' polishing; sector 3 shows the result of 120 seconds' polishing; sector 4 shows the result of 300 seconds' polishing; sector 5 shows the result of 1800 seconds' polishing.

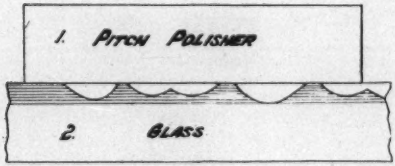

FIG. 7.

In sectors 1 and 2 the amount of scattered light is so great, owing to the large proportion of light scattering hollows that a good contrast under the microscope is not readily obtainable. In sectors 3, 4, and 5 the proportion of polished surfaces to hollows is so great that the desired contrast by suitable illumination is obtainable.

Similar series of photographs have been taken for various types of hard and soft glasses with various types of polishers and polishing media. In all cases the general characteristics are the same, and in no case is there any evidence of hollows or pits in the original Alpha glass being filled or covered over.

There is, of course, a well recognised difference between a soft cloth polished surface and a pitch polished surface. In the instance illustrated above, the cloth was of a very special kind hardly distinguishable in its effects from pitch.

Although the action of a soft cloth polisher is fundamentally the same as that of a pitch polisher, it is interesting from the practical point of view to consider the effects produced by the two materials.

In fig. 7, 1 is the pitch polisher, the surface of which is flat and comparatively unyielding, and 2 is the glass. Under the action of the polisher successive flat layers of the glass are

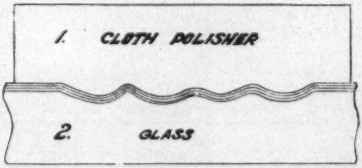

FIG. 8.

liquefied, broken up, and removed, as is indicated by the parallel horizontal lines.

In fig. 8 the soft cloth polisher comes into contact with the surfaces of the hollows, and the layers—indicated as before by the contour lines—are no longer flat, but follow approximately the original surface.

It is well known in the workshop that the irregularities of the surface can never be polished flat by means of a soft cloth polisher. Sinuosities having glazed surfaces always remain.

A surface that is not completely polished exhibits what is technically known as greyness when the polisher is a pitch one. The greyness is caused by scattered light from the hollows. If, at an earlier stage, say before sector 3 of

fig. 6, a soft cloth polisher had been used, the bottoms of the pits would have become glazed and at the later pitch stage the greyness would not have been readily observable. The pits, however, would still exist and would detract from the optical perfection of the surface. To remove them it would be necessary to remove the material beyond the bottom of the hollows with a pitch or equivalent tool.

It is commonly thought that a cloth polisher hastens the action. In reality a cloth polisher removes material more slowly than a pitch polisher. It only apparently hastens the action by masking the greyness and by creating the impression that the surface is finished before it actually is.

From the truly optical point of view it might even be preferable to leave the surface grey than to disguise the defects.

There are many kinds of optical work in which it is quite permissible to mask the greyness, in which case the use of cloth of varying hardness is advantageous.

For the production of a high quality optical surface in which masking of the greyness is not permissible, the use of a soft cloth polisher before the pitch polisher offers no advantages. It really only lengthens the time of polishing.

Quantities of the surface material removed by polishing have been collected and examined under the microscope, but a satisfactory micro-photograph suitable for reproduction has not been obtained owing to the want of contrast in the specimens.

The material was collected in the process of polishing the surface of a very obtuse angled prism by means of a pitch and rouge polisher. The material removed from the flat surface being polished accumulated in the form of a hard, cement-like layer on the inclined surface which was not in contact with the polisher.

When the rouge is dissolved out of the hard cement, an extremely fine, snow-like powder of

glass remains. Under the microscope this glass presents a complex appearance. There are numerous rounded grains of glass which it is interesting to note closely resemble in size and form the grains of the polishing medium. Indeed, so close is the resemblance that the glass grains can only be distinguished from the grains of rouge by the sparkling appearance of the former under suitable illumination.

There also appear flat patches apparently consisting of a large number of grains welded together. Whether separate grains have actually welded themselves together to form the patch or whether it is a portion of the surface layer that has been peeled off is not clear. The former assumption implies welding properties for which the author can offer no definite evidence. It is true that two flat polished surfaces of glass can be pressed into such intimate contact as to suggest a welding of the contact layers. When the two pieces of glass have different coefficients of expansion, they can be separated by the application of heat and the contact surfaces in general present their original appearance. When the pieces have the same expansion, to separate them may not be easy. If such surfaces could be separated it would be interesting to know if the contact layers have been actually welded.

In support of the latter assumption that the patch is a portion of the original surface layer of Beta glass, there is the common experience of the workshop that portions of the surface layer do peel off. Peeling of the surface is quite a well-known occurrence in the process of polishing glass.

By a fortunate chance the author is in possession of additional evidence in support of the statement that the polished surface consists of a definite layer of Beta glass having physical properties differing from the original Alpha glass and having a considerable thickness of about eight wave lengths.

A block of crown glass having polished and smoothed faces was heated to a temperature which appears to have been below the softening point of the Alpha glass and just above that of the Beta glass.

The smoothed unpolished surface remained unaltered, whereas the polished surface exhibited a network of grooves, due apparently to the softening and contraction of the Beta layer,

FIG. 9.—MAGNIFICATION 100 DIAMS.

in which there must evidently have been a considerable tension.

Fig. 9 is a photo-micrograph of the grooved surface, the magnification being 100 diams. The grooving has all the well known characteristics of the crazed surface of glazed pottery where the physical properties of the glaze differ from those of the underlying material.

For comparison a photograph of a typical

crazed pottery surface is represented in fig. 10.

In fig. 9 the uniform width of the individual lines suggests a uniform thickness of the layer.

It will be noticed also in both specimens that the grooves do not cross one another. A patch evidently cracks across as the result of contraction, thus forming two patches which in turn may each become subdivided. The wider grooves are probably those of earlier origin or are associated with large patches.

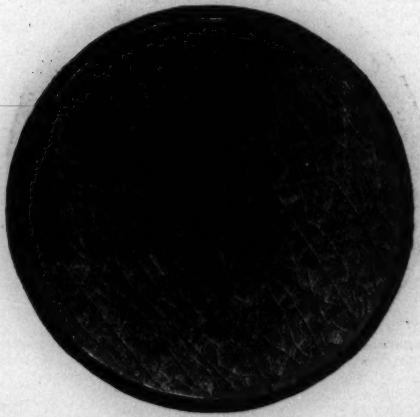

FIG. 10.—ACTUAL SIZE.

The microphotograph represents only one of a considerable number of samples that have been obtained, thus indicating that the grooving of the surface is quite a definite phenomenon. In order to measure the thickness of the surface layer as represented by the depths of the grooves, a transverse section of a specimen was polished and photographed. Fig. 11 is the

photo-micrograph in question, the magnification being 100 diameters. The central groove was cut very obliquely, and has accordingly a blunt "V" form.

The great majority of the groove sections examined were of practically one uniform depth. The depth of the groove, and presumably of the Beta layer, is between 1/4000th and 1/5000th inch (1/200th mm.), that is, about eight wave lengths.

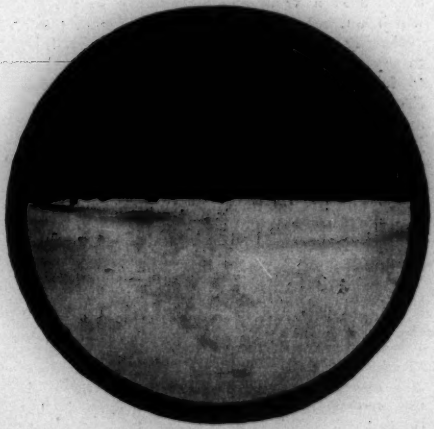

FIG. 11.—MAGNIFICATION 100 DIAMS.

From the workshop point of view the specimen illustrated by fig. 11 is remarkable on account of the very special skill involved in obtaining a clean edge that showed practically no rounding when examined with a test plate. The edge was not protected in any way, as is the common practice when preparing similar metal sections.

DISCUSSION.

Dr. Walter Rosenhain said the subject of grinding and polishing glass was one of great interest to all those engaged in the production and use of glass for optical purposes, and it was a subject which had not yet received the amount of study and attention which it undoubtedly deserved. The Society ought therefore to feel particularly grateful to Mr. French for the new facts contained in his paper, which undoubtedly constituted a valuable contribution to a field which had been too little cultivated in the past.

Having said that, he thought it only fair to say that he found himself rather at a loss to follow some of the arguments which Mr. French had used. In a great many cases, at any rate, he had not given sufficient evidence to justify the very sweeping conclusions he had enunciated. He probably possessed that evidence, but he certainly had not given it in his paper, and until it was forthcoming he, for one, thought it necessary to suspend judgment as to whether it was possible or not to accept the conclusions put forward in the paper.

He would take the points one by one, and to justify himself for speaking in this way he might perhaps recall to the minds of those present what many of them already knew, namely, that he had in the past himself devoted considerable attention to this particular question, and that some years since he had given a paper to the Optical Society on Polishing Materials and Abrasives, in which a great many of the facts quoted by Mr. French were very clearly stated and illustrated. Mr. French did not appear to be aware of the existence of that paper, and of several others in which this subject had been dealt with. However, that was a minor point.

First of all, Mr. French insisted rather strongly on the difference—a difference, he thought he suggested, in kind rather than degree—between the behaviour of glass and metals

during polishing. That there was a large difference was obvious to anyone who had worked with both kinds of materials, but he felt himself unable to accept, without a good deal of further proof, the view that the difference was so fundamental as was suggested by Mr. French. He had referred to Sir George Beilby's very beautiful evidence of the bridging over of holes and grooves in metal, and quoted certain facts which he considered disproved the possibility of the same things happening with regard to glass. In the first place, if one considered the relative properties of glass and of metals, their relative strength and relative brittleness, one would not expect to find anything like as much bridging action in the case of glass as in the case of metals. In metal itself the bridging action depended enormously upon the manner in which the polishing was done. As they all knew, it was perfectly possible to polish a piece of metal —most kinds of metal—by means of a burnishing tool, by simply rubbing the metal surface with a smooth steel object. In that case there was no removal of metal at all; all that happened was surface flow and surface deformation; the ridges were pressed down, the hollows were filled up, and a smooth, burnished surface was obtained. That was the condition of maximum flow—maximum bridging and minimum abrading.

On the other hand, if, in polishing a metal, a very hard abrasive or polishing material was used, a condition would be obtained of minimum flow; the harder the metal the less the flow in given conditions of polishing. If glass were looked upon as a particularly hard substance, it was easy to understand why there would be a good deal less flow in glass than in metal. But that the action of the pitch polisher depended entirely upon the removal of the ridges, and that it had to be carried absolutely below the level of the pits, was a matter which would, he thought, have to be proved, if it was

to be proved satisfactorily, by actual measurements. If Mr. French had in his possession definite evidence of that kind, he hoped he might see his way to communicate it. Failing that, judgment should be suspended on his conclusions.

There was one fundamental difference between metals and glass in regard to their behaviour on grinding, and it was really a difference of technique, perhaps, more than of physical properties. When metal was polished it was nearly always done with a fixed abrasive, generally a wheel, and each grain of the abrasive material occupied a certain definite position towards the metal which was being polished, and that polishing was done by a more or less linear motion and not by the swirling motion which was customary in the case of glass. Thus the surface of the metal was simply covered by a number of more or less parallel grooves, and when that was done conditions were obtained which were favourable first of all to the formation of grooves, then to their bridging over, and finally to their subsequent reappearance on etching. In the case of glass, on the other hand, which was ground with a loose abrasive, loosely held between the tool and the glass, and ground with a rotary motion, one did not get anything like the kind of regular pattern which was obtained in metal. What was obtained was a series of conchoidal fractures on the surface. But that was not necessarily the only thing that was obtained. Very likely there were also, underneath, hidden by these conchoidal markings, a series of chaotic scratches running about all over the surface; and he would suggest to Mr. French the possibility that it was those hidden, one might almost call them subcutaneous, scratches which reappeared on etching a polished surface of glass. Why Mr. French should conclude that these scratches resided merely in the surface layer he could not see, and there again he thought they must wait

for further evidence. At any rate, he would submit the other possibility for consideration.

Then he wished to draw attention to another point. Mr. French had throughout his paper entirely ignored the action of the polishing medium—rouge, or whatever else might be used. As they all knew, that did exert a very powerful influence, and the question was: What was its nature? To some extent no doubt it was mechanical, but he (Dr. Rosenhain) had long ago suggested, and still thought there was a very great deal to be said for the idea, that the polishing medium entered into the surface layer, that its action was like the action of any other impurity or dissolved body in facilitating molecular movement, and that the nature of the polishing material affected the ease with which molecules could be induced to leave their old allegiance and come under the influence of surface tension. Now if they believed that the polishing medium could enter into the composition of the glass either mechanically or chemically, then one piece of the evidence adduced by Mr. French fell to the ground. Mr. French laid a great deal of stress on the observation that he had never succeeded in including anything, even traces of silver, under a polished glass surface. He should be very much surprised if he had. Those very small amounts of foreign matter would intermingle with the flow of glass and would dissolve in the surface layer. If a piece of silver was polished with rouge of a particular kind, a perfectly beautiful polished surface was obtained. But if that was put aside in a desiccator for a few weeks, where no dust could reach it, then, after a time, particles of rouge would appear on the surface; the silver, which had absorbed them, had expelled them again. He had no definite evidence to show that such action occurred in the case of glass, but he did think that at any rate there was a considerable probability that it did.

Some evidence in support of that view was to

be found in the fact that the chemical behaviour of a glass surface varied appreciably with the kind of polishing material used; the behaviour of polished glass surfaces was distinctly different, according to the polishing material used, towards certain chemical reagents. Another thing to be borne in mind was that not every powder acted equally well as a polishing medium, and that was a fact which must play a vital part in the understanding of the processes which went on in polishing. All good polishing media belonged to the chemical group of oxides—rouge (oxide of iron), magnesia, alumina.

Then Mr. French had raised the question whether glass was capable of welding at ordinary temperatures. He thought in the first place the mere existence of a surface, or the mere fact that molecules once disturbed could readjust themselves in the same way as under the influence of fire polish, proved that they could weld on to the original glass surface; and if they could weld on to the original glass surface, why not on to each other? More than that, it was a well-known fact that the cut of a diamond, if allowed to rest for some time, ceased to be a cut.

A piece of thick glass on which a heavy diamond cut had been made, if tapped immediately afterwards, would break quite readily, but if left for a number of hours, depending on the temperature, the nature of the glass, the depth of the cut, and various other conditions, then the glass behaved as if it had been merely scratched. And he thought it had been ascertained, though he could not recall where or by whom, that the very fine fissure which resided at the bottom of a diamond cut actually healed up in the course of a certain number of hours. If that was the case, there was undoubtedly evidence of welding. Of course, there must be exclusion of air, but the fissure was so fine that probably air never entered it, and therefore welding could occur.

Perhaps the part of Mr. French's paper which had interested him most was that dealing with the evidence of the grooving of the surface layer as the result of heat. He had not stated the exact conditions, as to how hot the glass was made and so forth, all of which would have been extremely interesting to know, but it was in any case a most interesting observation. The only thing was he did not think they understood what it meant, and he could not at all follow Mr. French's explanation of it. If there was a discrete surface layer, and the whole thing was cooling down from a high temperature, and the surface layer contracted more than the interior, then it was easily understood that a "crazed" skin would be obtained. But if they noticed what the "craze' skin of the pottery was like, it had really only one resemblance to the grooves shown by Mr. French on the glass layer, and that was the absence of crossing of the various lines. That was quite an important thing, and proved that certain of the lines were formed before others, and that a line once formed somehow or other relieved the forces at work in forming the other lines. All he could say was that it was a most interesting observation, and one well worth following up. It suggested to him the possibility of observing the surface layer in transverse section. Mr. French, by a very beautiful example of polishing work, had shown that it was possible to obtain a transverse section in which these grooves were very clearly shown. Would it not be possible to examine such a transverse section in polarised light—he did not mean one in which the grooves had been produced by heating, but one in its normal, natural state—and to ascertain whether there was really a layer of strained glass on the surface?

He would not detain the meeting any longer, but the whole paper raised questions of very great interest indeed, and, as he had said already, they were much indebted to Mr. French

for having gone to the trouble of writing the paper and illustrating it so beautifully. He must express his particular admiration of the photographs, which were very clear and beautiful, and, as he could testify from his own experience, required considerable trouble and skill for their successful preparation. If he had felt it necessary to register his divergence of view in certain respects, he hoped that both the members present and Mr. French himself would realise that this was the sincerest mark he could offer of his appreciation of Mr. French's work.

Mr. P. F. Everitt said that with reference to the point raised with regard to the possibility of welding, many years ago it was quite a common thing that two pieces of the same kind of glass should be in optical contact so that there was no reflection of the surfaces; they might be left in that state for a few hours, or a few months, or a few years, and they could be separated again. It seemed to him that the point was whether the optical contact was a sufficiently close contact—whether there was a total exclusion of air or whether there were a few stray molecules left. It was a point that might perhaps be noted in connection with the remarks in the paper about the middle of p. 36. In the cases he referred to they were pieces of the same kind of glass, and frequently, but not necessarily, of the same melting.

The President: Mr. French is only talking about the separation, I think, there.

Mr. Everitt: He says "If such surfaces could be separated"—my point is that they can be.

The President: Separated after being welded. He admits the welding, I take it. The question is, if they could be separated, what would be the condition of the surfaces?

Mr. Everitt, continuing, said that one of Dr. Rosenhain's remarks appeared to throw some doubt on Mr. French's explanation of the removal of the glass till the bottom of the pit

was reached. With regard to that he might say that in polishing a sphere he had found that there was no possible doubt about the removal of the glass; the diameter of the glass sphere continually decreased, and in working to a very accurate size of sphere layer after layer was removed until the required size was obtained. It was possible, by means of the micrometer, to measure to within the $\frac{1}{10000}$ of an inch, or even finer, and the removal of the glass was perfectly easily seen. Even half an hour's polishing would reduce the diameter a measurable quantity.

Mr. T. Smith remarked that Dr. Rosenhain had said he could not quite agree with the theory advanced by the writer of the paper as to the action which took place in polishing. In that connection he thought some reference might have been made to a paper of Lord Rayleigh's on the subject. As far as he had noticed no reference had so far been made to that paper. Speaking from recollection he thought the conclusion to which Lord Rayleigh came was that there was a very decided difference between the actions of grinding and of polishing, and that polishing was not so much a removal of the surface as a means of causing a surface flow. The statement made by Mr. French that in order to get a good polish it was necessary to get right down to the bottom of a pit was contradictory to Lord Rayleigh's observation that he could get a satisfactory polish far short of that. It was not a polish, perhaps, that would satisfy the manufacturer of an optical instrument, because there was slight greyness in the surface, and its appearance was not as beautiful as was the work regularly turned out from a shop; but Lord Rayleigh found that without getting anywhere near the bottom of the pit he could get a satisfactory result as far as the optical properties of the instrument went.

The President: Was that with pitch or cloth?

Mr. Smith thought that conclusion applied to all the polishing materials that Lord Rayleigh

had tried. He believed that it was so stated in the paper, but he only spoke from recollection.

The PRESIDENT pointed out that Mr. French admitted it with regard to cloth—but was it so with regard to pitch?

MR. SMITH said that speaking from recollection he thought Lord Rayleigh's statement applied to polishing processes in general.

MR. H. R. FAIRBANKS said that all who had practical knowledge of glass-working must realise the very great value of Mr. French's paper to the whole of the optical industry. He well remembered Lord Rayleigh's lecture at the Northampton Institute on glass polishing, and according to his recollection Lord Rayleigh left it an open question whether the result of the polishing was a surface flow or whether it was removal from the surface. One point had been touched upon which must not be lost sight of, and that was the thorough knowledge which Mr. French had of the various means of polishing, compared with which the knowledge possessed by Lord Rayleigh at the time of his lecture must be admitted to be limited, although he, of course, did not wish to say one word against the thoroughness with which Lord Rayleigh always carried out any experiment he undertook. Mr. French had exhibited very clearly indeed the difference between a cloth and a pitch polisher —more clearly, he thought, than it had ever been shown before. With regard to his findings, although he admitted that he could not offer any actual evidence, yet some of his results seemed to show that, after all, what Lord Rayleigh had said years ago was true, namely: "Each of the two factors mentioned was to some extent responsible for the result that it arose partly from surface flow and partly from removal of the surface." He thought, moreover, Mr. French's paper showed that the action of the tool itself was a thing that counted as well as the actual polishing material.

Mr. S. D. Chalmers thought there was one difficulty arising from the way in which the subject had been presented, which might account for the differences of opinion expressed. What Mr. French had done had been to show that in the modern methods of glass polishing endeavour had been made to secure the polisher, and the method of polishing, which worked as far as possible by removal of the glass; but in the methods of polishing with cloth, and in a good deal of the older pitch polishing, there was a very great deal of surface flow. The efforts in the direction of the improvement of polishing had been to do away as far as possible with the filling up of gaps by the action of the polisher. He was quite certain that those who had had experience of the use of cloth polishers would agree that it was possible to get a definite condition of glass flowing over the holes. He thought Dr. Rosenhain would bear him out in stating that the common way of polishing metal did secure a perceptible flow over the surface, but that it was possible to reduce that to a very great extent by careful polishing. He thought the experience of workers on metal for optical purposes would confirm the view expressed by Mr. French that there was very little actual flow in that case. To his mind, what was really of importance in Mr. French's paper was that the thing to aim at in polishing a surface was to do as much work as possible by the removal of the surface instead of by inducing surface flow, and that when the figure was kept perfect they were really finding the conditions under which the polishing work was done by removal of material as far as possible. He believed that in much polishing work there was a certain amount of flow.

If a surface had to be burnished as rapidly as possible, it was quite easy, if those methods were used which were specially favourable to rapid polishing of the surface, to induce a flow of surface of very considerable magnitude. He believed that the action of polishing was to a large

extent chemical, and that the action of the polishing material, assisted by the local heating, caused the surface layer to become mobile; at the beginning of the polishing the peaks were exposed to the polishing material, were made more fluid, and were rubbed off as spherical globules. As the polishing proceeded the action was more widely extended, and the part of the surface which was made more liquid would flow, but it would not cross any unmodified area except as a bridge. If the methods of working which were specially favourable to "buffing up" a surface were used, it was possible to bridge over quite considerable marks without however completely filling up the holes. If the holes were to be filled up it was necessary to polish the bottoms of the holes while they were still below the general level. In this case he thought there would be a certain amount of flow, though it would not be sufficient to give a good surface; it was in fact intermediate between the burnishing and best optical polishing.

Progress in optical polishing seemed to be in the direction of securing more rapid removal of the material and the reduction of the flow which could take place before the whole surface was reduced to one level. He wished to express his appreciation of Mr. French's careful observations and experiments.

Dr. R. S. Clay said there appeared to be some misapprehension as to what was meant by optical contact. Optical contact really meant that the surfaces were so close to one another that the light reflected from the upper surface was opposite in phase, or nearly so, to the light reflected from the lower one and a black image resulted. That did not mean that the two surfaces absolutely touched one another; it meant that they were so close to each other that their distance apart was small compared with the wave length of light. The wave-length of light was a very large thing compared to the distance apart of the molecules of glass, and therefore to get two

surfaces into welding contact meant getting them much closer than was necessary merely to produce the optical black spot. Measurements had been made of soap-bubble films which showed a black spot. The thickness was quite appreciable, and contained a large number of molecules; so that two surfaces could be separated by a distance comparable to the space occupied by perhaps twenty to thirty molecules and yet be in "optical contact." Many of them had seen examples of two lenses so firmly attached to one another that one was broken in trying to get them apart; there was no cementing, of course, and that was quite a common occurrence. Dr. Rosenhain, in speaking of the "crazing" of pottery, and comparing it with the scratches which Mr. French obtained, appeared to have difficulty in seeing how the surface was going to be broken by tensions. But it was quite conceivable that the surface layer might have a smaller co-efficient of expansion than that of the natural, undisturbed glass, and if so the mere heating of the glass would cause it to expand less rapidly than the lower layers, and this would cause the cracks to form; then if the temperature was sufficient to cause a slight flow it would produce the effect shown by the illustration.

Continuing, he said that he also remembered hearing Lord Rayleigh's paper, and it seemed to him that nothing said on that occasion was at all inconsistent with what Mr. French now stated, namely, that it was necessary to polish down to the bottoms of the pits, because Lord Rayleigh had said that he did find some greyness left, which meant that the bottoms of the pits were still in existence and were producing the greyness he described.

Mr. A. H. Emerson said that with reference to surface flow there was one factor that had not been mentioned. Experimenters had noticed that surface flow took place a great deal more rapidly when the surface was heated. He also suggested that the fact of the surface fracture

being shown was not perhaps a proof that the surface layer was different from the other. If a piece of glass was raised to a sufficiently high temperature devitrification would take place, and a similar result would follow.

Mr. T. F. Connolly wished to refer to a matter already mentioned by Dr. Clay, namely, the difficulty suggested as between the observations of Lord Rayleigh and those of Mr. French. Mr. French's photographic plates clearly showed that five seconds' polishing gave a polish satisfactory to a limited extent; while Lord Rayleigh had pointed out that a very slight amount of polishing removed the smallest pits and gave a polish that would pass, though it might possibly not be accepted as being optically good. The removal of deeper pits was a much longer operation. That seemed to him to afford an instance of striking reconciliation between the conclusions of the two observers, rather than of any divergence.

As to the origin of the scratches or markings shown after etching, Mr. French suggested that the Beta layer of glass had a very definite thickness—something of the order of $\frac{3}{10000}$ to $\frac{5}{10000}$ of an inch. Whether the scratches originated in the Beta layer or below would be revealed by measurements made before and after etching. If the scratches were subcutaneous, it should be a very easy matter to recognise their point of origin by mechanical or by optical measurement, which would show a diminution of substance, and the discrepancy or difficulty ought not to exist any longer than the time it would take to make a measurement of not extreme accuracy, say $\frac{8}{10000}$ to $\frac{4}{10000}$ of an inch.

The President said he understood that there were quite a number of gentlemen present who were experienced polishers, and Mr. Chalmers had suggested to him that he should invite opinions from them as to whether surface flow did or did not take place during the polishing process.

Mr. Everitt thought that if the President's question was to be properly answered, account

must be taken of the different methods of polishing.

Prof. W. E. Oakden said it had occurred to him that several of these difficulties or problems might be solved by making a few practical experiments. Instead of having a more or less level or even surface, experiments might be made on a sort of fluted surface. It might be moulded in the first instance, and fluted to different degrees, and polished with a soft felt or a hard pitch polisher. Of course the pitch polisher necessarily could not come into contact with the hollows; it would have to operate on the ridges of the polished surface. With such a piece of fluted glass, the polishing could be carried on either crosswise or lengthwise with different kinds of polishers, and this, in his opinion, would solve some of the difficulties or problems alluded to in the paper and in the discussion.

Mr. E. Boul said that in polishing lenses he had noticed that in some cases there was a surface flow and in other cases a removal of the material. He had also made windows which, after being ground were too large for their receptacles, but after polishing with cloth sufficient of the surface had been removed to enable them to be fitted into the places prepared for them.

Mr. Shackleton asked whether the same polisher had been used in the case of surface flow as in the case of removal of material.

Mr. Boul replied he had noticed a removal of material with both cloth and pitch polishing, but only in the case of cloth polishing had the surface flow been observed.

Mr. F. E. Lamplough said it would be very interesting to know whether the same kind of markings were obtained in glass polished with a cloth polisher and with a pitch polisher, and in an untouched fractured surface. He was not going to put forward a view in opposition to that advanced by Mr. French, but there seemed to be another possible explanation. It required a fairly high temperature to produce such mark-

ings, and it was just possible that some surface chemical or physical change might take place—perhaps volatilisation—which would produce a volume change, and in that way result in fissures.

The PRESIDENT, in moving that the best thanks of the meeting be given to the author of the paper, said he was sure they would all agree that it had been an ideal paper for such a society as theirs. It had been an exceedingly interesting paper, carefully thought out, and a very large amount of experimental work had been done in connection with it. Mr. French was the practical scientific adviser of the firm of Barr & Stroud, and he might say, without divulging any trade secret, that the grinding and polishing operations carried on by that firm were probably equal, if not superior, in extent and importance to those of any other concern in the world. They had developed those operations to an extraordinary extent, and Mr. French had been very largely identified with the work; so they might take it without any shadow of doubt that it was an expert who was speaking to them on that particular subject.

With regard to the question raised as to whether it was necssary to polish down to the bottom of a pit in order to remove the pit, he would take the earliest possible opportunity of asking Mr. French to furnish the evidence for which Dr. Rosenhain had asked, and he was quite sure he would be only too willing to give it.

He was afraid he could not add much that was of value to the discussion, but he might perhaps touch upon one point. Galileo was an independent inventor of the telescope, and had done a large amount of valuable work with a telescope not so good as it was possible to make in these days at the cost of a shilling. Galileo was succeeded as a maker of telescopes by Campana, who made object glasses up to three or four inches in diameter. The task of polishing lenses of that size was exceedingly formidable, but Campana discovered a method of polishing that no one else

could equal, and the result was that for a long time he was the finest maker of telescope objectives in the world. He kept his secret until his death. After his death of course many people were anxious to examine his workshop and find out his secret. That secret turned out to be a very simple one. After he had roughed his lens by grinding, he lined the roughing tool with paper and polished with rouge in the ordinary way. He believed Newton was the inventor of the pitch process, and anyone who read Newton's Optics would quickly understand why it was necessary that this process should be invented. The question was often asked how it was that Newton did not discover the Fraunhofer lines, but anyone who read Newton's description of the "magnificent" prisms supplied from abroad would understand the difficulty. He believed that upon one occasion the Customs had put an embargo upon the delivery of these prisms until duty had been paid, and Newton was asked what was the value of the prisms. He replied that they were "absolutely priceless." Of course the Customs authorities were in a difficulty, and did not know how to appraise the value of things which were absolutely priceless. But Newton went on to describe those prisms, and it was quite clear that even the very best prisms then obtainable had a large portion of the surface filled up with pits, and from Newton's own description the polishing went down to the bottom of the pit and climbed up almost perpendicularly on the other side.

The vote of thanks to Mr. French was then put to the meeting and carried by acclamation.

AUTHOR'S REPLY.

Mr. French writes:—I wish to thank the members for the interest they have taken in the subject of my paper, and for the kind way in which they have discussed the various statements made therein. Particularly I wish to thank Dr. Rosenhain for his frank and searching criticisms. It appears that in some respects

our views are directly opposed, and I quite agree that where such opposition exists the proofs should be definite and ample.

It is desirable, of course, if satisfactory conclusions are to be attained, that proofs should be advanced from both points of view. For example, Dr. Rosenhain, I understand, doubts my statement that sleeks are associated with the Beta layer alone, and that there is no visible covering over of grooves or pits in the underlying Alpha material. Now, I can produce many specimens that confirm my statement, whereas, although my opportunities for examination are exceptionally favourable, I have never seen a polished glass specimen the surface of which covered over visible foreign matter of external origin. Can Dr. Rosenhain produce any normal specimens of this kind in support of his contention?

The statement that to obtain a perfectly polished glass surface the material has to be removed beyond the level of the deepest pits is also questioned by Dr. Rosenhain. The statement is, I find, not a novel one; it was very definitely made by Lord Rayleigh in 1905, and I think I need not do more than quote as follows from his lecture of that year, as delivered before the Optical Convention:—

> "But I must say that in my experience with glass—and my experience was limited to glass—I never saw anything to suggest that idea" (that idea of the filling up and covering over of pits), "and my impression is that no material once removed is deposited again, and that the process of polishing has to be continued until all the glass is worn down to the level of the deepest pits."

When I wrote my paper I was unaware of the above-quoted statement by Lord Rayleigh, and the similarity of the wording is accordingly noteworthy. I was under the impression that the polishing action described by Sir George

Beilby in the case of metals was being applied to glass. Such a view, I thought, might lead the manufacturer to underestimate the importance of fine smoothing operations, and it was for that reason I emphasised the statement by italicising it. Notwithstanding the fact that sleeks in the Beta glass are filled in, though not bridged over, if of greater width than at the most one or two wave-lengths, I do not think that Lord Rayleigh's statement requires any modification, not even the opinion that "no material once removed is deposited again." I hope at an early date to give some details of the filling in of sleeks and of the material that is removed, as I have now succeeded in obtaining satisfactory photomicrographs suitable for reproduction.

Dr. Rosenhain suggests that the scratches that reappear on etching may have their origin in possibly a series of chaotic scratches running about all over the surface, but under the Beta layer. If a perfect pitch-polished surface be examined after very slight etching there will probably be seen a few straight edged sleeks, or surface layer crack marks. The portions of such lines that are reproduced generally appear straight, but I have obtained specimens of curved sleeks, and also a specimen which shows a sleek originating at a surface defect. I do not think I have ever seen a surface that showed on etching a series of chaotic scratches. It may be argued that only a few of the chaotic scratches may at first appear. There is, however, no evidence, so far as I have observed, of such scratches coming into view. When the surface is etched a number of line markings may instantly make their appearance. If the etching process is continued the original lines and markings will still be present in the form of ever-broadening chains of pools, but no new markings will make their appearance. If a soft cloth polished surface be etched there will also be observed numerous isolated pools or groups

of pools corresponding with the original conchoidal sinuosities of the surface. Further, it would be noticed that the sleeks and markings in many cases intersected one another. This, I think, would not be the case if they originated as Alpha glass cracks, because one crack is generally terminated by a transverse one.

And again, the exposed Beta layer markings have no resemblance to the cracks that occur in the Alpha glass. To classify and describe the types of sleeks and cracks common to the Beta layer, and the cracks or cleavages common to the original Alpha glass would require a separate paper. The one outstanding feature is the dissimilarity of the two sets.

In a well-regulated smoothing or grinding process with loose abrasive, where the temperature differences are small, I do not think the Alpha material is traversed by a chaotic series of possibly healed up cracks. That a crack may close and become invisible is unquestioned, but in my experience so-called healed cracks are likely to re-open, and the piece should therefore be rejected in the first instance. It is remarkable how few cracks of any importance occur in the smoothing of glass. When, however, heat is generated by the abrasive action there is considerable danger of the formation of cracks. During a considerable number of years I have had much experience in the grinding of glass by means of abrasive wheels, the glass being operated upon somewhat in the same manner as steel. Large quantities of the finest optical work have been produced in this way. Unless special precautions are taken the heat generated as the result of wheel irregularities gives rise to small fractures of the glass, and although some of these cracks may heal and not reappear, it too frequently happens that such flaws develop.

Dr. Rosenhain directs attention to the polishing medium, the action of which he considers may be chemical. Personally, I think the

action is mechanical, at least very largely so. On the other hand, the chemical theory is a possible and attractive one, and indeed there are certain curious phenomena that may be more readily explained by it. I think Dr. Rosenhain misunderstands my position when he says that to believe in the mechanical or chemical mixture of the polishing medium with the glass means the falling to the ground of one piece of the evidence adduced by me. I presume Dr. Rosenhain refers to molecular intermingling. If visible matter is entrained in or under the surface layer, why is it not seen? That molecular particles may be entrained is conceivable. What I believe is that the cohesion of the silicates or other substances constituting the surface layer is so small as to prevent the bridging over of gaps in which visible foreign matter can rest. I believe that the surface layer can be filled into gaps such as sleeks in the surface layer itself. From observation I believe that sleeks having a width of two wave-lengths, or possibly one, are not bridged over. Beyond that I have no evidence. It is quite possible that ultramicroscopic gaps, or possibly gaps under two wave-lengths, but not more, may be bridged over. It is entirely a question of degree. It is conceivable and not inconsistent with my expressed views that molecules of foreign matter may be entrained in the Beta layer and covered over.

Dr. Rosenhain has drawn attention to the well-known fact that the best polishing media belong to the chemical group of oxides. It is interesting to note in this connection that glass can be polished without the use of any oxide as a polishing medium. The rate of polishing is very slow, but the glass can be polished. I am very interested in the statement that the chemical behaviour of a glass surface varies appreciably with the kind of polishing material used. If Dr. Rosenhain would be so kind as to give further details as to the reagents employed and

the chemical behaviours, I should be very glad to have an opportunity of repeating the experiments, as so important a feature may be capable of practical development.

Dr. Rosenhain's suggested experiment of examining the polished surface layer by polarised light, as viewed through a transverse section, is one that I have frequently made, especially for the examination of ground glass surfaces. I have, however, repeated the experiment with a specimen having a surface highly polished with maximum pressure and drag and having a particularly sharp and clean transverse edge. Under the surface there was a distinct white line suggestive of strain when the Nicols were crossed. But it would not be wise to assume from this evidence that the surface layer is stressed, as I have reason to think it is. The white line may be due wholly or in part to light at scraping incidence reflected internally from and polarised by the polished surface. If a ground surface is examined in the same way quite a distinct fringe of polarised light will be seen. Here again the polarised light may be due to stress in the material or wholly or partly to reflection and polarisation of light from the internal conchoidal glazed surfaces, particularly at the entering and leaving edges, or possibly to the penetration of light reflected at scraping incidence from the outer surface. The last supposition is improbable, because when the outer surface is painted black there is no appreciable change of appearance. Any surface cracks can very readily be observed by polarised light in the manner described. As already stated, it is remarkable how seldom such cracks occur in the case of glass ground under conditions in which undue irregularities of temperature are prevented.

In reply to Mr. Everitt, I can confirm his statement regarding the actual removal of material during polishing. It did not occur to me that such removal would be questioned, be-

cause the fact is so easily confirmed. As Mr. Everitt states, the amount removed in half-an-hour is a measurable quantity. A good average reduction of size in the case of optical plate glass when using pitch and rouge by hand, under ordinary workshop conditions, is 1/10,000 inch per half-hour.

In reply to Mr. Smith, I must apologise for not having first made myself thoroughly familiar with the somewhat limited literature of my subject. In the past it is the practical aspects of optics that have interested me most. I have now read Lord Rayleigh's lectures, and in doing so I have realised how clearly and definitely he has outlined some of the principal features of the polishing process. I am glad to know that in general my observations confirm his. I do not think Mr. Smith has reason to say that my statement that in order to get a good polish it was necessary to get right down to the bottom of a pit was contradictory to Lord Rayleigh's observation that he could get a satisfactory polish far short of that. It is a question of degree. For instance, I could show Mr. Smith a perfect image reflected from a rough ground surface of glass, but one would not call such a surface sufficiently good for an optical instrument. Similarly, although a grey surface might be sufficiently good from the point of view of the amateur, it would not be advisable for a manufacturer to submit optical parts showing the smallest trace of greyness to a Woolwich Arsenal Inspector. They would be quite rightly rejected. It is as easy to produce a properly polished surface as to produce a grey one.

In reply to Mr. Fairbanks, I hope to show in a paper which I may have the honour of submitting at an early date to the members of the Optical Society that both surface flow and removal of material occur together during the polishing of glass surfaces. I hope in that paper to give photographs and measurements of the particles that are removed. It is only recently

that I have succeeded in obtaining satisfactory photomicrographs, owing to want of contrast in the specimens.

In reply to Mr. Chalmers, I would repeat what I have stated above, that in polishing glass, both surface flow and removal of material occur together. At one stage of the polishing process, in the case of pitch tools, the operation is deliberately manipulated so as to give maximum drag and minimum removal, but I believe there is in practice always some removal of material. Actually the surface flow drag is, I believe, greater in the case of a pitch polisher than in the case of a soft cloth polisher. With a cloth polisher the removal of material is quite considerable and easily measurable. I think only an expert could distinguish between a surface polished without final drag and one finished by final dragging of the surface layer. By close examination the difference is quite evident. I hope my next paper will supply answers to Mr. Chalmers' other questions. I shall endeavour to make clear to him what is the real nature of the supposed covering-over of holes. If Mr. Chalmers considers it is "possible to bridge over quite considerable marks," I should be very pleased if he would kindly send me a specimen for examination.

Dr. Clay's remarks on optical contact, which I have read with much interest, do not call for special reply. With regard to the crazing of the optical surface, I hope in my next lecture to exhibit some remarkable specimens, which incidentally will throw light on the strength of the Beta layer. In view of these specimens I have no doubt the physical properties of the Beta material are very different from those of the original glass.

In reply to Mr. Emerson, I did not know it had been demonstrated by experimenters that surface flow took place a great deal more rapidly when the surface was heated. The statement is very interesting. That heat has some effect is

quite probable; what that effect is quantitatively I do not know. It is certainly not essential to the polishing process. In the factory the temperature is controlled. If the temperature fluctuates, difficulty will be experienced in regulating the figure. I have always regarded undue temperature as being undesirable. The question is, however, one well worth further investigation.

In reply to Mr. Connolly, the thickness of the Beta layer, as measured by me, is about 1/200 mm., that is, about eight wave-lengths. In my paper the dimension five wave-lengths was mentioned in error as being the equivalent of 1/200 mm. The measurements suggested by Mr. Connolly have been repeatedly carried out by me. In all cases the figures given by me are based upon precise measurements. Had I anticipated the keen interest of the members in this subject of optical polishing I would probably have made my lecture of more practical interest by the inclusion of figures. This I hope to do in my next paper. In this connection I may say that for this work I have had constructed a set of electric micrometers, for which a difference of 1/50,000 inch is a coarse measurement. The zero can also be set sufficiently accurately to give an absolute measurement of 1/50,000 inch.

In reply to Professor Oakden, a piece of glass roughed with carborundum and polished with soft cloth has a glazed surface that resembles the fine skin of an orange. The finest grade of rouge has particles having dimensions of three or four wave-lengths, and some of the particles are even smaller. The sinuosities of the type of surface mentioned above are such that a hard pitch tool does not sink into the hollows and come into contact with their surfaces, as is the case with cloth. If the tool is removed, the fine grain of rouge can be seen lying quite undisturbed deep down in the hollows. When the surface is partly polished, the appearance is striking, and, I

think, convincing. The perfection of the polished patches is indeed astonishing. I shall endeavour to include a specimen in my next paper.

With Mr. Boul's remarks I entirely agree, except possibly in one small detail. I think there is always some removal of material; I cannot see how it is to be entirely avoided.

Mr. Lamplough has raised a question of much importance. I have already realised the importance of obtaining the same markings on glass polished in various ways as well as on natural fractured surfaces and on fire-glazed surfaces. But to obtain such specimens is not easy. The ones I have were the result of a lucky chance. I fear I shall have to wait and watch patiently for the others I so much desire. The specimens I have were polished with both cloth and pitch, but I expect the character of the surface was largely determined by the pitch.

In conclusion, I wish to thank our President for his very kind remarks, and I wish again to thank the members for the generous way in which they have discussed my statements, so many of which I recognise to be highly controversial. I did not anticipate that certain points such as the removal of material, would be doubted. Had I done so I would have endeavoured to make my paper more conclusive. With the kind permission of the President and members, I hope I may have the honour of remedying that deficiency at an early date. I would take the opportunity of exhibiting at the same time some remarkable photographs which I think may help one who is prepared to acknowledge the existence of the Beta layer to realise how different from ordinary glass and how fragile the surface material is.

SCIENCE AND INDUSTRY (**BEAMA**, January 16).—By the courtesy of the Editor of "The Beama Journal," the Society is able to reprint below the portion of the article dealing with the Optical Industry, by the late Prof. Silvanus P. Thompson, F.R.S., which appeared in the January number of the British Electrical and Allied Manufacturers' Association's Journal.

. . . . . Let me turn to a different chapter in the relations of science to industry. There is no industry in England to-day which presents a more deplorable picture of the results of failure to co-operate for national and common good than does the glass industry. It is in few hands; its businesses are for the most part old established concerns enjoying considerable reputation, managed by partners or directors of unquestionable integrity, who have for years been faced with difficulties attendant on production, difficulties such as few others have had to encounter in the way of restrictions imposed by the trade unions. The Glass Workers' Union is notorious as probably the most obstructive and unpatriotic in England. Glass workers have indeed a black chapter of setbacks to British trade to their discredit, not the least of these being their recurrent opposition to the introduction of scientific improvements. This has reacted on industrial progress. What would be the use of manufacturers laying out capital on making improvements in their plant, and on their methods, if they were to be for ever thwarted by the uninformed opposition of the workers? It is an old tale, this complaint of the supineness of the masters and the obstructiveness of the men. Result: foreign glass works, in which scientific development is possible, progressing by leaps and bounds; while cheap imported glassware injures branch after branch of British

manufacture. For over thirty years the telescope makers have been complaining that they have not been able to get glass discs suitable for making the lenses of large telescopes. English glass-makers could not or would not be at the trouble of such manufacture; the demand would be too small. Why, the total requirement would not amount to five tons per annum of this sort of glass. Let the French makers make it. The makers of thermometers needed a special sort of glass which should be able to withstand rapid heating and cooling without showing as most glass does, a persistent contraction when cold. Would the glass manufacturers in Great Britain trouble to make such a glass or permit their works' chemists to spend time on search for the best composition for this purpose? Not they; let the thermometer trade go to Thuringia, and let English factories be relieved of any bother of chemical research. Are steam gauges wanted of a glass that will endure hot water uncorroded? Send to Germany for them. Are glass chimneys needed, of special glass to withstand cracking when used to protect gas-mantles? Here was a new branch of industry arising out of the invention of the incandescent mantle. Who would discover the best kind of glass or the most expeditious way of blowing those shades? Oh, leave it to Holland or to Saxony. The chemical analysis would cost too much; and moreover our workmen would oppose any improved method of blowing the glass. Is special baryta crown glass wanted for the best kinds of camera lenses? Oh, the baryta ore in the English market is not pure enough; and, besides, special melting pots would be needed. Don't let us trouble about it: let the opticians import it from abroad. Then the war breaks out, and we discover serious shortages in optical glass, in thermometers, in chemical glassware, in steam-gauges, in lamp chimneys, and in a score of other glass commodities, the manufacture of which has been driven out of England.

Two decades ago there came along an inventor

to whom there had occurred the idea of making an unbreakable glass for factory-windows or roofs by embedding wire netting in the substance of the sheet. An excellent notion; and entirely practicable, as the inventor finds from a few specimens which, not without some coaxing and pushing—and at his own expense—he has at last persuaded a leading British firm of manufacturers (and keen tariff reformers a few years later) to make for him as samples. So far, so well: but it was a wholly different matter to induce any firm of British glass-makers to take up the new line of manufacture. Messrs. X of London, and Messrs. Y of Birmingham, and Messrs. Z of Lancashire are much too well off, and too satisfied with their own trade, to father a new British industry. There is nothing here to appeal to the greedy imagination of the company-promoter in the City. And so after disheartening months have elapsed the patentee drops his patents. Less than two years go by, and this very product of unbreakable glass is boomed upon the British market as the last new Yankee invention; while it is triumphantly announced that the leading firm of Messrs. Z of Lancashire will act as agents for its importation into Great Britain.

But why should one stop reciting such stories? Only last month it was announced that a certain American glass works, after considerable research and scientific study with the spectroscope, have just discovered a blue-green sort of glass which, when used for the bulbs of tungsten filament lamps causes their light to resemble daylight—the very quality of light desirable for lighting picture-galleries and studios. Doubtless to the credit of the American. Doubtless also, to the discredit of those British lamp firms who two years ago were themselves ahead in this matter, were two years ago using in this country a glass of similar properties—and have now ceased to manufacture such lamps! Why, I myself opened a discussion on the merits of these daylight lamps at the Society of Illuminating Engineers nearly two years ago. Now that British makers have

dropped them, we shall probably see them shortly imported from America as being the latest novelty in lamps. One reason why they have been dropped here is that the commercial travellers know no science: a reproach also too true in almost every industry, and doubly disastrous in foreign trade, where the travellers of foreign competitors are mostly men technically trained, as well as good linguists.

Incidents of this kind do not encourage men of scientific training to regard hopefully the attitude of British manufacturers. Whatever betterment the future may witness, the past has been disastrous enough. And not in the electric line, or in the glass line alone. Let the story of the British dye-stuff industry, and of its decay, be once more a warning. The indigo planter of India, and the woad farmer of Wisbeach, interested parties both, denounced the chemically manufactured dyes, however pure, as an inferior imitation, regardless of the fact that the chemist had discovered literally hundreds of new dye-stuffs, some indeed fugitive, others more permanent than woad, or indigo, or madder. How the German dye-stuff industry flourished by the cultivation of science, and the British industry languished by its neglect, is an oft-told tale. The sugar-refining industry and the synthetic drug industry are, alas, mere chapters in the same catalogue of disasters. Belittle the teachings of science; ignore the expert trained in science; carry on your works without him; if you must have him, pay him less wages than you pay a fitter; put him under non-technical directors and managers who know no science. Then, when, after years of this neglect, your chickens come home to roost, and you find that the progress which ought to have been made here is made in foreign countries instead, blame the patent laws, blame the lack of protective tariffs, blame the Trades Unions. Blame everything and anything except the chiefest cause—the blindness of manufacturers and men to the truth that *that industry is doomed whose leaders despise and neglect*

science. It was so before the war; it will be so after it.

To remedy this state of things much is needed. (i.) A remodelling of all education in all branches, to remove the disadvantages which arise from men devoid of any idea of scientific method growing up into civil and industrial life. (ii.) A reconstruction of the Universities as centres of earnest work from which idlers and triflers are rigidly excluded. (iii.) A radical change in the meaning borne by University degrees, to ensure that they shall be the mark of thorough training under competent teachers, and not mere attestations of cleverness in passing examinations; so that men shall wish to go to a University, not in order to get a degree, but to receive there a training infinitely more valuable than any letters after their names. All this is preliminary and will take years to produce its full effect. The industries must make more use of such aids as are afforded by the laboratory departments of the Universities and Technical Colleges. What the National Physical Laboratory has done in aid of the scientific industries at large, the local laboratories of the Colleges may do on a small scale for local industries. And the leaders in the industrial world must see to it that the local Universities do not degenerate into degree-grinding cramshops, but that they take (as for instance the University of Sheffield is taking) an effective part in helping the scientific advancement of the local industry. In turn, it will richly repay the industries to help the laboratories of the Colleges, to equip them thoroughly, and to ensure that they are directed by men who carry scientific weight. A very significant movement is already in progress in the United States. There, to a degree unheard of in Britain, it has been for many years the practice of some of the great industrial concerns, in engineering, metallurgy and the chemical manufactures, to ally themselves with the Universities, both by aiding to equip the laboratories, and by competing amongst themselves to

secure the ablest graduates as assistants on their staffs. This method of bringing science into the factory by securing highly trained young men to become the future heads of departments and managers, and chiefs of staff, has been of enormous advantage, yet it has not been found sufficient. Several of the largest and most prominent of manufacturing organisations have now found it expedient to equip and maintain elaborate research departments and scientific laboratories in the factory, to push forward scientific advances within the industry. And the research department not only undertakes researches, involving time and money and trained ability, but helps to perfect the scientific and technical qualifications of the younger assistants. More remarkable still, members of these research staffs are allowed and encouraged to publish from time to time bulletins of the scientific and technical advances so maintained. The two great electrical organisations in the States—the General Electric Company of Schenectady, and the Westinghouse Electric Manufacturing Company of Pittsburg, have led the way in this enlightened policy. Not one of our English-grown industrial concerns has anything like this to show. We are twenty years behind the States in our appreciation of the importance of science to industry. Perhaps it is equally true to say that in our Universities we are twenty years behind in our appreciation of the importance of the industries to science; even so this is but a part of the failure of the nation at large to grasp the fundamental importance of scientific training.

Until we have made good our backwardness and blindness it will be mostly idle to talk of Great Britain capturing the industries which have been destroyed on the Continent of Europe by the great war. If she could capture them she could not maintain that capture, her factories not being staffed with men of scientific training. You cannot in a year, no nor in two years or three, train up a staff of men to scientific thinking or working, any more than you could train

these same men to be violinists capable of playing in an orchestra. Neither can factory laboratories be created out of hand. They must grow and develop according to progressive industrial needs; and the men to develop them must themselves be evolved. They cannot be imported ready-made from the Universities or Colleges: neither can they be produced from the ranks of a commercial staff, even the ablest, if untrained in science. In persistent collaboration and co-operation of industry with science lies the road to progress. W. S.

ANNEALING GLASS (**NAT.**, October 26th).—Prof. C. V. Boys calls attention to a method of annealing glass in which any strain may be observed in the cooling glass throughout the range of critical temperatures. In the case of all glasses there is a temperature above which they must be heated in order that the subsequent slow cooling may anneal effectively. This temperature differs as much as 200° C. for the various optical glasses, and may be much below any visible softening point. When the temperatures have dropped below certain values, at which the glasses have lost all viscosity, the rate of cooling may be greatly increased, as any strain due to unequal cooling is only temporary.

Messrs. Hilger have, after careful investigation, found the means of arriving at the maximum temperature necessary, and also the necessary rate of cooling, which may progressively become more rapid.

In the method of observing strain, the glass with polished edges, to transmit a beam of polarised light broken up into parallel interference bands by a Babinet's compensator, is heated in an electric muffle furnace, the temperature of which is observed by an electric thermometer. The displacement of the interference bands transmitted through the glass is proportional to the strain. By inducing a definite amount of strain into the glass by mechanical means, for example by bending, the rate at which the glass relieves itself of the strain may be observed for any temperature.

By watching the bands in specimens of glass Messrs. Hilger are able to ascertain when the glass is hot enough to allow the internal strains to be relieved in a convenient time, and whether as the glass cools internal strains are avoided by sufficiently slow cooling.

As a result of these investigations it has been

shown how annealing may be perfectly effected in a minimum time. With the apparatus erected in their laboratory Messrs. Hilger are prepared to test specimens for the trade.

T. F. C.

"On the Theory of Optical Instruments with Automatic Focusing of Image and Object." (**ZEIT. für INST.**, October).—Dr. H. Lehmann describes the geometrical construction connecting the successive positions of object and image in automatic focusing devices. More than once he acknowledges these are well known in England, but novel in Germany. He describes geometrical constructions by Pizzighelli, Carpentier, Killian, and Sampson, and shows how they can be applied to "scissors" linkwork or trammels, in one case so accurately that even a final touch by hand is unnecessary.

Illustrations are also given of models for purposes of instruction, which show the necessary linkwork to maintain the object and image in conjugate positions.

Enlarging cameras embodying similar principles are already on the market in this country, and the variable power telescope which remains in focus throughout the changes of magnification is another application. The article is to be continued, and will be abstracted more fully when complete.

W. S.